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Impetus then and now:
A detailed comparison between Jean Buridan and a single contemporary subject

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Conceptual change in mechanics can neither be understood nor facilitated without knowledge of the content and structure of the common sense beliefs with which it starts. However, empirical investigations of common sense beliefs about physical motion have not yet produced a consensus about the correct characterization of such beliefs. Different researchers have proposed different hypothesis about the content of common sense beliefs, about their relations to historical theories in physics, and about the reasoning processes available to scientifically naive persons. The empirical validity of the alternative claims are difficult to appraise because many published reports give little information about how well the various hypotheses account for the data on which they are said to be based. In this paper we apply a four-step method to the analysis of a single interview protocol in order to answer three questions: (a) What, exactly, does the subject believe about physical motion? (b) What is the relation between the subject's common sense beliefs and the impetus theory of physical motion formulated by the philosopher Jean Buridan in the fourteenth century? and (c) What theoretical reasoning processes, if any, does the subject have at her disposal for reasoning about physical motion? The results show

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Knowledge and Understanding in Human Learning

Knowledge and Understanding in Human Learning (KUL) is an umbrella term for a loosely connected set of activities lead by Stellan Ohlsson at the Learning Research and Development Center, University of Pittsburgh. The aim of KUL is to clarify the role of *world knowledge* in human thinking, reasoning, and problem solving. World knowledge consists of concepts and principles, and contrasts with facts (episodic knowledge) and with cognitive skills (procedural knowledge). The long term goal is to answer six questions: How can the concepts and principles of particular domains be identified? How are concepts and principles acquired? How can the acquisition of concepts and principles be assessed? How are concepts and principles encoded in the mind? How are concepts and principles utilized in performance and learning? How can instruction facilitate the acquisition and utilization of concepts and principles (as opposed to episodic or procedural knowledge)? Different methodologies are used to investigate these questions: Psychological experiments, protocol studies, computer simulations, historical studies, semantic, logical, and mathematical analyses, instructional intervention studies, and so on. A list of KUL reports appear at the back of this report.

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Abstract

Conceptual change in mechanics can neither be understood nor facilitated without knowledge of the content and structure of the common sense beliefs with which it starts. However, empirical investigations of common sense beliefs about physical motion have not yet produced a consensus about the correct characterization of such beliefs. Different researchers have proposed different hypotheses about the content of common sense beliefs, about their relations to historical theories in physics, and about the reasoning processes available to scientifically naive persons. The empirical validity of the alternative claims are difficult to appraise because many published reports give little information about how well the various hypotheses account for the data on which they are said to be based. In this paper we apply a four-step method to the analysis of a single interview protocol in order to answer three questions: (a) What, exactly, does the subject believe about physical motion? (b) What is the relation between the subject's common sense beliefs and the impetus theory of physical motion formulated by the philosopher Jean Buridan in the fourteenth century? and (c) What theoretical reasoning processes, if any, does the subject have at her disposal for reasoning about physical motion? The results show that the subject believes in a version of the impetus theory, that her theory overlaps with the theory proposed by Buridan but is nevertheless not identical to it, and that the subject is able to reason theoretically in at least the following ways: to compare alternative hypotheses about a phenomenon, to generate a prediction from a counterfactual assumption, to carry out *reductio ad absurdum* arguments, and to evaluate the consistency of a hypothesis with respect to a range of phenomena. Our results are consistent with the notion that scientifically naive subjects have theories about physical motion, but that their theories differ from those proposed by physicists, either in modern or historical times, to a greater greater or lesser extent.

Research Questions

Conceptual change in mechanics can neither be understood nor facilitated without knowledge of the content and structure of the common sense beliefs with which it starts. If common sense beliefs are closely related to the theories proposed by physicists before Newton, then the historical study of conceptual change in physics and the psychological study of conceptual change in the classroom might mutually support each other. But different studies have resulted in different descriptions of the content of common sense beliefs in mechanics (Champagne, Gunstone, & Klopfer, 1983; Champagne, Klopfer, Solomon, & Cahn, 1980; Clement, 1983; diSessa, 1983, 1988; Fischbein, Stavy, & Ma-Naim, 1987; Hailoun & Hestenes, 1985; McClosky, 1983a, 1983b; Nersessian & Resnick, 1989; Schecker, 1985) Both diSessa (1983, 1988) and Hestenes (1987) have questioned the appropriateness of ascribing *any* kind of theory of physical motion to students, on the grounds that their reasoning processes lack the consistency and systematicity that characterize theoretical thinking. The pedagogical implications of research on common sense beliefs are not yet clear.

Many reports of studies of physics beliefs lack information about how the data were processed, how the beliefs were identified, and by what criterion those beliefs were ascribed (or not ascribed) to the subjects. Many historical claims are equally unsupported. Global classifications like "Aristotelian theory" or "impetus theory" or "medieval beliefs" are frequently used without description of which beliefs are meant, and studies that do describe the supposed beliefs of pre-Newton physicists do not always cite the historical sources on which the descriptions are based. Finally, the claim that students' thinking is too unsystematic to warrant the characterization of common sense belief systems as theories has not yet been supported by empirical evidence.

This paper presents an analysis of a single contemporary subject. The purpose of the study is to answer three questions: What is the content of the subject's beliefs about physical motion? What is the relation between her beliefs and the theory proposed by the 14th century philosopher and scientist Jean Buridan? What reasoning processes does the subject employ in thinking about physical motion? To anticipate, our results show that our subject holds an impetus theory closely related to Buridan's, and that she is capable of theoretical thinking.

Method

The data presented here are drawn from a larger study in which six subjects were interviewed about physical motion. The subjects were University of Pittsburgh undergraduate students who participated in the study to fulfill a psychology course requirement. All six subjects had studied physics in either high school or college.

The first author met with each subject individually. The interview had a semi-structured format and was intended to explore the subjects' qualitative beliefs about physical motion. Each subject was presented with a succession of eight pictures (see Appendix A):

1. A large boulder suspended in the sky.
2. A plane flying in the air.
3. An elephant and a feather with dashed lines above each. The dashed lines give the appearance, cartoon-fashion, that the objects are falling.
4. A boy with a raised arm and a ball directly above him. Dashed lines between the boy and the ball indicate that he has just thrown the ball up in the air.
5. A cannon ball in front of a cannon. Dashed lines indicate that the ball has been shot from the cannon. The cannon is at an acute angle to the ground.
6. A person swinging a string or rope above her head. One end of the rope is in her hand and the other end is attached to a book-like object.
7. Two trucks at the top of two separate hills. One hill is steeper than the other. Each truck face the bottom of the hill.
8. A ball in a cylindrical tube. The ball is on the wall inside the tube.

The interviewer began the conversation about each picture by asking the subject to describe what he/she saw in the picture. The purpose of this step was to elicit the subject's spontaneous terminology for talking about physical motion. The interviewer adhered to this terminology in the subsequent questioning, to the extent possible. A fixed set of initial questions was used for each picture. The subject's answers to the initial questions were explored with follow-up questions. The conversation continued until the interviewer felt that the initial questions had been answered as fully as the subject was able, at which point the interviewer presented the next picture and asked the subject to describe it. This process continued through the eight pictures. Each interview lasted approximately an hour (58--72 min.). The interviews were tape-recorded and transcribed verbatim. The length of the protocols ranged between 985 and 1500 lines.

Results

For purposes of this paper, we focus on a single subject, called S4. We identify her beliefs, and compare them to the theory proposed by Jean Buridan. Finally, we briefly investigate her reasoning processes.

Identifying S4's beliefs

The method used to identify S4's beliefs consisted of four steps: *breakdown*, *interpretation*, *abstraction*, and *focussing*. Each step is explained and illustrated below.

Step 1: Protocol breakdown. In the first step of the analysis the entire protocol was broken down into single lines or sequences of lines in which a single idea is expressed. We call those *interpretable passages*. The goal of this step was to identify the *shortest* passages that contained enough context to allow interpretation of what the subject was saying. Consequently, the length of the passages varied with the clarity of the subject's expression; occasionally single lines were interpretable; typically more context was needed. We did not try to formulate a formal criterion of interpretability; the breakdown was done intuitively.

For example, the following protocol segment was broken down into two interpretable passages, 523-534 and 535-541:

523 I: Okay. What do you see in this picture?
524 S: A boy throws a rock, I guess, and it comes back
525 down and hits him.
526 I: Okay. Um, imagine that he's throwing this rock
527 straight up.
528 S: Mmm-hmm.
529 I: What will happen?
530 S: It will fall back down, straight down.
531 I: Okay. And so, he'll get hit?
532 S: Well, it will hit the ground. It will hit the
533 ground. It will come right back where it came from,
534 like a boomerang.

535 I: Um, what causes the object, the rock, to turn
536 back down to the ground?
537 S: Gravitation. The force that the little boy
538 uses to throw the rock, I guess, only carries enough
539 energy for the rock to, uh, to go against the
540 gravitational pull for a certain amount, you know, for a
541 certain amount of space.

The 1085 lines of S4's protocol were partitioned into 101 interpretable passages. To facilitate further analysis, each passage was written on a single notecard in NOTECARDS, a hypertext system available on Xerox 1186 workstations.

Step 2: Interpretation. In this step the 101 passages identified in Step 1 were interpreted. For each passage a short text--usually a single sentence--was created which tersely formulated what the subject seemed to us to be saying in that passage. Each passage was interpreted in isolation from the other passages, to the extent possible.

For example, the passage 523-534 shown above was interpreted as: *A rock thrown directly up will come directly back down like a boomerang and hit the ground*

The passage 535-541 was interpreted as: *The thrown rock comes back down because the force of the thrower provides a certain amount of energy to the rock, and that energy can only go against the gravitational pull for a limited distance*

The purpose of the interpretation step was to express the content of each protocol passage as clearly and directly as possible, eliminating the question-and-answer structure of the actual protocol passages, as well as the pauses, false starts, repetitions, slips of the tongue, and ambiguities that characterize spoken language. The referents of the subject's utterances were not changed. If the subject spoke about *trucks* in a particular passage, the interpretation of that passage was formulated in terms of trucks as well; if the subject spoke about *objects*, the interpretation was formulated in terms of objects, and so on. There is a one-one relation between passages and interpretations, i. e., each passage received only one interpretation. The interpretations were recorded on notecards in the NOTECARD system. The interpretations were constructed by passing the NOTECARD file back and forth between the two authors, each author revising and rewriting the interpretations until all disagreements were resolved. On a small number of occasions the effort to interpret the passages lead to a revision of the boundaries between the interpretable passages. The intersubjective reliability of the interpretations could, in principle, be validated by asking independent judges to estimate the faithfulness of each interpretation to the corresponding passage, but we have not yet carried out such a validation.

Step 3: Abstraction. The third step in the analysis had two goals. First, although the interpretations of many passages consist of a single sentence, they nevertheless typically expressed more than one proposition. So the first purpose of this step was to decompose each interpretation into its component propositions. Second, the subject did not have beliefs about the *particular* objects in the pictures shown during the interviews. The pictures were schematic line drawings without pretense to realism. For instance, the picture of a boy throwing a rock shows a fictitious rock-throwing event never before seen by the subject. She could not have any beliefs about *that* rock, *that* boy, or about *that* throw. Consequently, we interpret her statements about the picture as expressing general beliefs about thrown objects. So the second purpose was to generalize over the particular objects and events discussed during the interview by replacing concrete terms such as "rock" with general terms such as "object". The decomposition and generalization operations were carried out on the interpretations of the protocol passages. The passages themselves were only consulted in case of disagreement between the authors as to how the interpretation should be analyzed.

For example, the interpretation of passage 535-541 shown above was decomposed into the following four general propositions:

1. *Imparted momentum/force/energy keeps an object moving after the source of the momentum/force/energy has ceased to act on the object.* (This belief was also expressed in six other interpretations.)
2. *An agent imparts momentum/force/energy to the object it acts on.* (This belief was expressed in six other interpretations.)
3. *Stronger momentum/force/energy enables an object to travel a longer distance.* (This belief was also expressed in six other interpretations.)
4. *For an object to move (in any other direction than downwards), it must be propelled by a force that is stronger than gravity.* (This belief was also expressed in eight other interpretations.)

The language of the beliefs conformed to the language used by the subject, to the extent possible. The phrase momentum/force/energy is used to indicate that she used the three terms "momentum", "force", and "energy" interchangably in the set of protocol passages that supports these propositions.

The abstraction step yielded a set of 92 propositions. When we write about S4's beliefs in the following, we are referring to the propositions in this set. If the protocol passages constitute our raw data, then the list of these 92 beliefs constitutes our processed data. Appendix B contains the entire set of 92 beliefs. We did not try to construct causal networks like those proposed by Clement (1979) on the basis of these beliefs. The beliefs themselves are the units of analysis used in answering our research questions. Each belief was written on a single notecard in the NOTECARD system.

Since a single interpretation is decomposed into a set of one or more beliefs, it may seem as if the relation between interpretations and beliefs is a one-many mapping. Hence, the number of beliefs should be greater than the number of interpretations. But in our analysis, 101 interpretations gave rise to 92 beliefs. The reason is that the subject expressed the same belief in the discussion of more than one picture, or in more than one way while discussing a single picture. A particular belief can thus result from the analysis of more than one interpretation. Thus, the relation between interpretations and beliefs is a many-many mapping, each interpretation typically being analyzed into more than one belief and each belief typically occurring in the analysis of more than one interpretation. The NOTECARD system turned out to be an indispensible tool for keeping track of the relations between passages, interpretations, and beliefs. Figure 1 shows a graphical representation of the relations between the different steps in the analysis.

Step 4: Focussing. All 92 beliefs are not equally well supported by the protocol. The majority of beliefs (51, or 57 %) occur in only a single passage. In order to focus on a set of well supported beliefs, we counted the number of different protocol passages in which each belief was expressed. (This was simple to do in the NOTECARD system: We simply counted the number of link-symbols on each relevant card.) Selecting *five or more occurrences* as our criterion of good support resulted in the following set of ten well supported beliefs, in order of frequency of occurrence:

1. *For an object to move (in any other direction than downwards), it must be propelled by a force that is stronger than gravity.*
2. *An object that is moving downwards due to gravity accumulates momentum/force/energy.*
3. *Imparted momentum/force/energy keeps an object moving after the source of the momentum/force/energy has ceased to act on the object.*
4. *An agent imparts momentum/force/energy to the object it acts on.*
5. *Stronger momentum/force/energy enables an object to travel a longer distance.*
6. *If there is no gravity, then objects float (in space).*
7. *Energy/force dissipates as it moves an object, unless it is replenished.*
8. *Gravity pulls things down.*
9. *The gravitational pull on an object is directly proportional to its weight.*
10. *The downward path of a projectile is not necessarily the same as the upward path.*

These are the beliefs which S4 appeals to most often in answering the interview questions. Although a belief is sometimes expressed more than once within a single context, each of these ten beliefs occur in the discussion of two or more pictures.

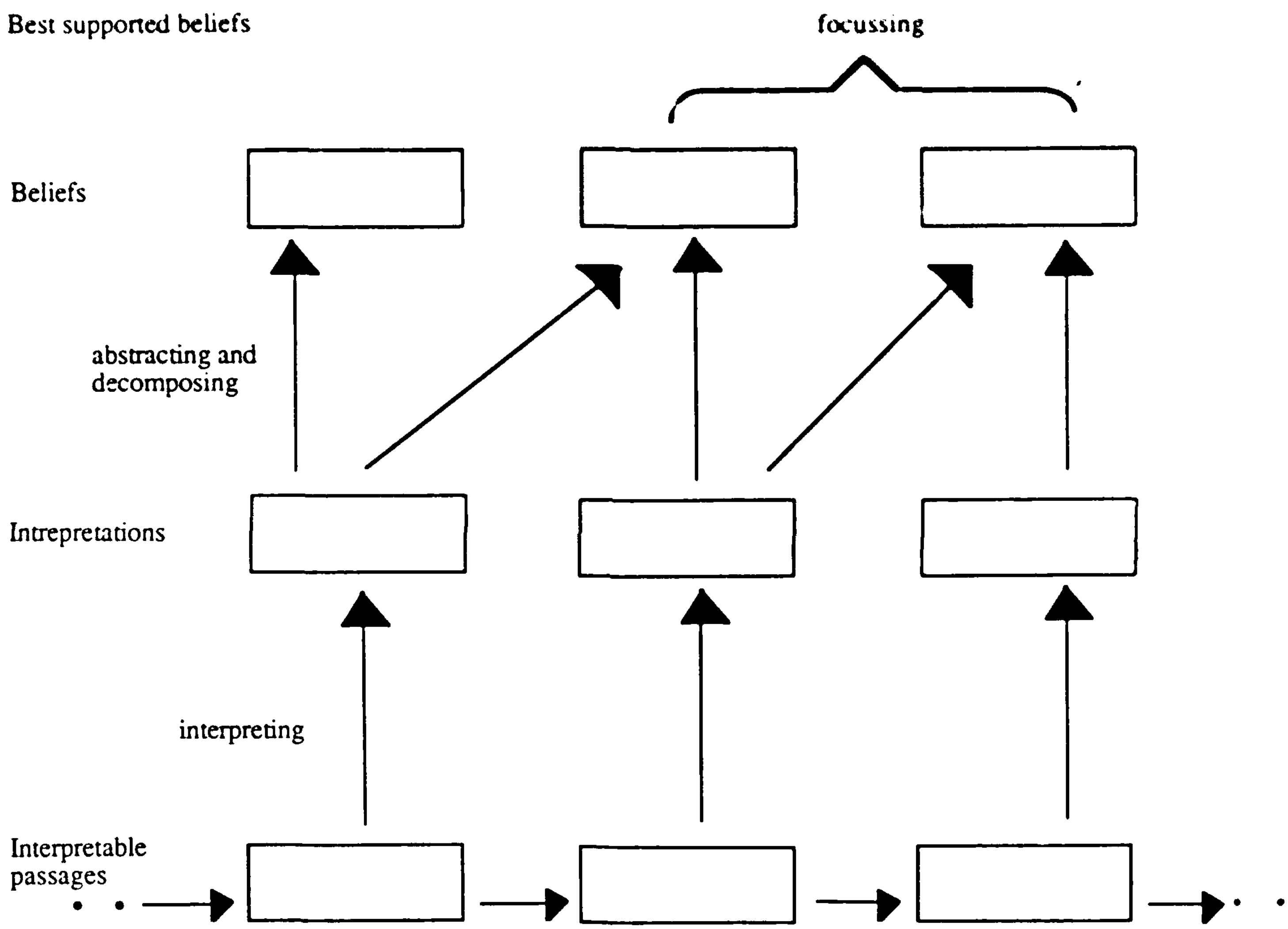

Figure 1. Graphical overview of method used to analyze the interview protocols. See text for explanation.

Table 1. Number of beliefs in three categories: (a) beliefs which subject S4 and Jean Buridan share, (b) beliefs with which Buridan would disagree, and (c) beliefs for which information about Buridan is missing, for each of seven topics.

Topic	Shared	Disagree	No info.	Sum
A. Force and motion	12	3	0	15
B. Downward motion	12	4	4	20
C. Gravity	10	11	0	21
D. Projectile motion	3	1	4	8
E. Space	0	2	1	3
F. Rotation	3	1	1	5
G. Floating	0	2	5	7
H. Flying	0	2	8	10
I. Miscellaneous	0	0	3	3
Sum	40	26	26	92

The relation between S4 and Jean Buridan

We compared S4's beliefs with statements from two texts by the 14th century scientist and philosopher Jean Buridan, *Questions on the Eight Books of the Physics of Aristotle* and *Questions on the Four Books on the Heavens and the World of Aristotle*. Being weak on Latin, we used the English translations in Claggett (1959, pp. 532-538 and pp. 557-562).

A belief of S4 and a text-passage from Buridan were recorded as *agreeing* if they describe or account for the same set of phenomena in the same way or if they entail the same phenomena. They were recorded as *disagreeing* if they implied different states of the world. A belief from S4 for which no related statement by Buridan could be found was recorded as *unrelated*.

The results were as follows: Of the set of ten well-supported beliefs listed above, seven are in agreement with Buridan's texts (1, 2, 3, 4, 5, 8, and 9). Two of the ten well supported beliefs are in disagreement with Buridan (6 and 7), and only belief 10 was classified as unrelated. Of the entire set of 92 beliefs attributed to S4, 40 beliefs (43 %) are in agreement with Buridan's statements about motion. Another 26 beliefs (28 %) disagree with Buridan's predictions and explanations of motion. Finally, 26 of S4's beliefs (28 %) are unrelated to Buridan's discussions of motion. Appendix B shows which beliefs were classified in each category. Table 1 shows the breakdown of these figures over seven topics. Examples from each category are presented below.

Examples of agreements between S4 and Buridan:

1. *S4*: Imparted momentum/force/energy keeps an object moving after the source of the momentum/force/energy has ceased to act on the object.

   Buridan: "Thus we can and ought to say that in the stone or other projectile, there is impressed something which is the motive force of that projectile.... It is by that impetus that the stone is moved after the projector ceases to move." (Clagett, 1959, pp. 534-535)

2. *S4*: An agent imparts momentum/force/energy to the object it acts on.

   Buridan: "Therefore, it seems to me that it ought to be said that the motor in moving a moving body impresses in it a certain impetus or a certain motive force of the moving body, in the direction toward which the mover was moving the moving body, either up or down, or laterally, or circularly." (Clagett, 1959, p. 534)

3. *S4*: Stronger momentum/force/energy enables an object to travel a longer distance

   Buridan: "And so also if light wood and heavy iron of the same volume and of the same shape are moved equally fast by a projector, the iron will be moved farther because there is impressed in it a more intense impetus, which is not so quickly corrupted as the lesser impetus would be corrupted." (Claggett, 1959, p. 535)

4. *S4*: The greater the height from which an object falls, the harder it falls.

Buridan: ". . .that by the amount that a stone descends over a greater distance and falls on a man, by that amount does it more seriously injure him." (Claggett, 1959, p. 557)

Examples of disagreements between S4 and Buridan:

1. *S4*: Energy/force dissipates even in the absence of resistance to the motion.

   Buridan: " ... God, when He created the world, moved each of the celestial orbs as he pleased, and in moving them He impressed in them impetuses which moved them without his having to move them any more ...And these impetuses which He impressed in the celestial bodies were not decreased nor corrupted afterwards, because there was no inclination of the celestial bodies for other movements. Nor was there resistance which would be corruptive or repressive of that impetus." (Claggett, 1959, p. 536)

2. *S4*: Gravity is a pull from the center of the earth.

   Buridan: "From these [suppositions] it is concluded that another moving force concurs in that movement beyond the natural gravity which was moving [the body] from the beginning and which remains always the same. Then finally I say that this other mover is not the place which attracts the heavy body as the magnet does the iron; nor is it some force existing in the place and arising either from the heavens or from something else, because it would immediately follow that the same heavy body would begin to be moved more swiftly from a low place than from a high one...

   From these [reasons] it follows that one must imagine that a heavy body not only acquires motion unto itself from its principal mover, i.e., its gravity, but that it also acquires unto itself a certain impetus with that motion. This impetus has the power of moving the heavy body in conjunction with the permanent natural gravity. And because that impetus is acquired in common with motion, hence the swifter the motion is, the greater and stronger the impetus is. . . .And just as the impetus is acquired in common with motion, so it is decreased or becomes deficient in common with the decrease and deficiency of the motion." (Claggett, 1959, pp. 560-561)

The beliefs expressed by S4 which were classified as unrelated to Buridan's theory dealt mainly with topics outside Buridan's concerns, such as floating and flying. For instance, one of the beliefs we identified for S4 was that *water produces a* *floating force that acts in the opposite direction of gravity.* We could not find any corresponding statement by Buridan.

In summary, the majority of those beliefs for which comparable passages could be found in Buridan's texts agree with those texts, including seven of the best-supported beliefs. The most important disagreements concern the role of resistance in the diminishing of impetus and the nature of gravity.

S4's reasoning processes

In order to provide some information about S4's reasoning processes, we scanned the protocol for instances of theoretical thinking. We did not attempt to define theoretical thinking. Instead, we searched the protocol for instances of commonly recognized theoretical thought processes. We will present five instances by quoting each relevant protocol passage.

Instance 1: Alternative hypotheses/suspension of judgement. In the context of Picture 1 (a rock in the air above an ocean), S4 is asked why the moon does not fall. She responds:

95 Well the moon isn't, isn't subjected to gravity, and that's
96 really the only thing that makes things fall, as far as the
97 earth, and the moon isn't within our gravity pull so
98 there's nowhere to fall. Besides, I mean, I
99 would guess so. It's either that, it doesn't have
100 gravity, it, or it doesn't have grav-.. At least, I know
101 that it's not in our gravitational pull, but if it does,
102 maybe it has gravity equal. You know what I mean.
103 What would make it pull in one direction there's an
104 equal gravitational force pulling it in the other direc-
105 tion. That would keep it still too. I don't know which
106 it is, but that makes sense. I mean, that's what I would
107 guess, my limited knowledge.

In lines 95-98 S4 says that the moon does not fall because it is not subject to the earth's gravitational pull. She then posits an alternative hypothesis: that two equal gravitational pulls in opposite directions would also prevent the moon from falling (101-105), adding that her limited knowledge does not enable her to decide which of the two hypotheses is correct (105-107). This passage shows that she is capable of considering alternative hypotheses for one and the same phenomenon and of suspending judgment in the absence of evidence.

Instance 2: Reductio ad absurdum. In response to the question "Does gravity act on all objects at all times?", S4 answers:

396 Hmm, well, I guess it does because although, for
397 example, birds, although they can, you know, lift
398 off the ground and fly, if there, if it wasn't acting
399 on them, once they lifted off the ground and [fly],
401: they would just disappear into space, and they don't.

Here S4 infers that gravity must act on birds while they are flying, because if it did not, they would disappear into space, and it can be observed that they do not; hence, gravity does act on them. This is a straightforward *reductio* argument.

Instance 3: Counterfactual reasoning/prediction. In the context of Picture 4 (a boy throwing a rock straight up into the air) S4 is asked the question "What causes the object, the rock, to turn back down to the ground?". She responds:

537 Gravitation. The force that the little boy uses to throw
538 the rock, I guess, only carries enough energy for the
539 rock to, uh, to go against the gravitational pull for a
540 certain amount, you know, for a certain amount of
541 space. ...
544 I know if he were a stronger boy, he
545 could probably throw it up higher, which means it
546 would be able to break it for much longer and much
547 further, or go against the pull from further than a
548 weaker throw.

In 537-544 she produces her answer to the question. She then continues in 544-548 with a thought experiment. She considers another situation than the one ostensibly shown in the picture (another, stronger boy), and applies her explanation to generate a prediction about that situation (the rock would be able to go against the gravitational pull much longer).

Instance 4: Empirical validation/consistency. In the context of Picture 2 (an airplane flying), S4 is asked what keeps airplanes and birds in the air. Her initial response is that "the wings must have something to do with it", but she also notices in passing that a person cannot fly by using his or her arms as wings ("if a person would rip out his arm imitating wings, the same thing would not happen"). After being probed about helicopters (which do not have wings) S4 changes focus and says:

149 Well, I guess it would take a lot of force, at
150 least for something man-made to go up in the air, which
151 is pro-, I mean, I'm not sure about helicopters, but I
152 know you have to gain a certain amount of speed before a
153 plane can elevate itself, and it's an incredible amount
154 of speed, so maybe a great amount of speed or force can,

155 you know, overrule the gravitational pull.

She immediately realizes that this hypothesis does not fit the case of a bird; five protocol lines further down, she says "that wouldn't explain the bird". She tries one more hypothesis, before she gives up:

170 Maybe the smaller the object, the less force
171 it takes. But then that wouldn't explain why a person
172 couldn't do it and a bird could. I don't know, I don't know.

It is noteworthy that S4 does *not* respond to the questions by simply proclaiming that planes fly in one way, birds in another, and helicopters in a third. She understands that a single explanation should cover all the relevant facts.

Instance 5: Empirical validation/consistency. In the context of Picture 3 (an elephant and a feather falling) S4 was asked the question "What is different about these two objects?" She answered that "it would seem that the elephant would fall a lot faster and a lot harder." She believed this because "leaves fall very gracefully and they kind of float back and forth. They don't fall like a rock." At this point she does not provide an explanation for the difference, but subsequent protocol passages show that she believed that the difference between these objects was due to the difference in their weights. When asked which object would fall quicker, an adult elephant or a baby elephant, she says:

210 Hmm, no. No, I guess I change my theory. (chuckles)
211 Well, I guess not, I mean, because I mean I couldn't
212 really see that [-] those people.. I think if a, if a person
213 would fall off a building, whether he's an adult or a
214 child, I really don't think there would be much of a
215 difference, so I guess that's wrong. Maybe it's the
216 density of something that affects the way it falls
217 instead of.. [Not] that I really know anything about
218 density, but I mean, maybe that has more of a
219 difference than actual literally weight because I don't
220 see any difference.

In this passage S4 rejects the hypothesis that differences in speed of falling are caused by differences in weight, on the grounds that an adult and a child would not fall with different speeds, in spite of the difference in weight (212-215). But she does not simply reject the weight hypothesis, she also posits an alternative hypothesis: that differences in speed of falling are due to differences in density (215-217). S4 rejects her weight hypothesis because it is inconsistent with the empirical phenomena (as she sees them) and searches for some other explanation.

However, S4 does not keep the density hypothesis for long. At a later point in the protocol, she tries to answer why an elephant and a book fall differently. She states that when a leaf falls, there is little damage to the leaf, but when a book or person falls, there is more damage. This leads her to the realization that "you sometimes judge it by the result, whether it remains intact or not, how it's falling" (272-274). At this point, she seems to be at an impasse. After a long pause, she says:

281 But I know that when you're in space, you're
282 weightless, right? So, when there's no gravitational..
283 Oh, that's right. Yeah, when you're in.. (chuckles) When
284 there's no gravitational pull, there's no weight, right?
285 [-] objects float around or whatever, so I guess, so
286 weight has to make a difference in gravity.

Once more, she revises her hypothesis in light of the facts (as she sees them). It is particularly noteworthy that S4 does *not* respond to her difficulties in explaining differences in speed of falling by simply declaring that weight plays a role sometimes and does not play a role at other times. On the contrary, she acts as if she believes that a single hypothesis should cover all the facts.

In summary, the protocol excerpts in this section show that S4 is capable of entertaining alternative hypotheses for a phenomenon, of suspending judgement in the face of insufficient evidence, of constructing *reductio ad absurdum* arguments, of counterfactual reasoning, of making predictions, and of rejecting hypotheses when they contradict the facts. All of these are commonly recognized components of theoretical thinking. Also, she understands that hypotheses must be consistent with all the facts for which they are relevant. The excerpts do not contain information about how frequently S4 employs these reasoning processes outside the laboratory, but they do show that she is *capable* of theoretical thinking.

Discussion and Conclusions

Our results show that S4 believes in a version of the impetus theory. Her beliefs 4 and 7 (see above) are the two principles identified by McClosky (1983, p. 306) as the fundamental principles of an impetus theory. S4's belief system belongs in the same family as the other common sense theories described in the literature, but it is not identical to any of them. For instance, S4's belief 3 is similar to the belief IB3 (*Continuing motion is sustained by a stored "force"*) reported by Nersessian and Resnick (1989, p. 415); their belief IB2 (*Motion is caused by "force"*)--previously reported by Schecker (1985, p. 286)--was also expressed by our subject, albeit not in one of the ten best supported beliefs. But their belief IB1 (*All motion requires a causal explanation*) is absent from S4's protocol. Furthermore, S4 expressed the Aristotelian belief that gravitational pull is proportional to weight (belief 9), but she did not express the Aristotelian principle that constant motion requires constant force, a common sense belief observed by several researchers (Champagne, Gunstone, & Klopfer, 1983; Halloun & Hestenes, 1987). These differences are undoubtedly due in part to genuine differences between the subjects in the different studies, and in part due to differences in the methods used to elicit the beliefs.

There is considerable overlap between Buridan and S4. However, there are also important differences between them. First, they differ with respect to specific issues in the theory of motion. For example, S4 holds that motion always peters out eventually while Buridan believes that motion is brought to an end by resistance. Consequently, Buridan predicts that infinite motion is possible, at least in the resistance-free heavens, while S4 states that everything must eventually come to rest, including a cannonball fired in outer space. It is a common finding that contemporary subjects are equally divided between these two versions of the impetus theory (see, e. g., Fischbein, Stavy, and Ma-Naim, 1987; McClosky, 1983).

A deeper difference is that S4's and Buridan's beliefs about motion are embedded within different world views, different assumptions about the nature of space and the structure of the universe. For example, Buridan adheres to the Aristotelian principle that the earth is fundamentally different from the planets and the stars. There is no evidence in S4's protocol that she believes that the objects in space are different in kind from those on earth. As a second example, Buridan believes that *gravitas* is a property of bodies on earth which causes them to move to the center of the earth. The more matter a body has, the more *gravitas* it has. S4, on the other hand, holds that gravity is a pull from the earth, and that the more matter there is, the greater the pull. *Gravitas* and gravity are thus ontologically different, although they play similar roles in the two belief systems. This situation caused us considerable confusion in the comparison between S4 and Buridan. We resolved it by regarding two beliefs as agreeing, if substituting *gravitas* for gravitational pull (or *vice versa*) made them agree. The complicated question whether two beliefs can be said to be the same if they are embedded in different world views cannot be addressed in the present paper.

The fact that one of our subjects is an impetus theoretician does not, of course, contain any information about the frequency distribution of impetus ideas in the population at large, or even in the population of undergraduate students. We are not claiming that S4 is a prototypical case. On the contrary, the data from our other subjects (to be reported elswhere) support the point already made in the comparison between S4 and Buridan: Belief systems that share a family resemblance can differ with respect to particular beliefs. For example, one of our other subjects, S3, frequently made use of a density argument similar to that employed by Galileo in *De Motu* to explain the rate at which bodies fall, a type of argument that was completely absent from S4's protocol. In short, our data supports the finding by McClosky (1983) and others that individual differences are the rule in common sense beliefs about motion. We are dealing with families or spaces of related, but not identical, belief systems.

Our results have several methodological implications. First, we want to argue that the individual person should be the macro-unit of analysis in studies of belief systems. Studies of physics beliefs often report aggregated data, e. g., frequencies of particular responses summed across subjects; also, data are frequently reported in terms of the question or test item used to elicit them. These practices ignore the fact that belief systems are *systems*, and that we need to know which beliefs or responses co-occur with which other beliefs or responses in a single mind. Second, we want to argue that the single belief should be the micro-unit of analysis of belief systems. Global classifications like "Aristotelian" or "impetus theory" are too course to be useful, except as short-hand. A description of a belief system must list its constituent beliefs and their relationships. This requires reliable methods for uncovering particular beliefs in data, and precise criteria for ascribing those beliefs and relationships to subjects. Third, since individual differences are ubiquitous, we need to develop methods for describing spaces of beliefs systems that are globally related but differ in their details.

It is quite plausible that different belief systems have different potential for change. For instance, consider the difference between Buridan and S4 with respect to resistance: If impetus diminishes spontaneously, as S4 believes, then infinite motion is not possible. If, on the other hand, impetus is corrupted by resistance, as Buridan believes, then infinite motion is possible in a resistance-free environment. It seems plausible that the second of these beliefs is more conducive to discovering or grasping the principle of inertia than the first. In general, the possibilities for change are to some extent constrained and shaped by the starting point. Hence, studies of the fine-grained differences in content between individual belief systems might turn out to be crucial for understanding belief change in mechanics; global characterizations may not be enough.

The second main determinant of belief change is of course the cognitive processes involved in reasoning about motion. diSessa (1983, 1988) has argued that although students' interview answers resemble statements by earlier generations of physicists, it is inappropriate to characterize their belief systems as *theories*, on the grounds that their thought processes lack the concern for consistency and systematicity that characterize theoretical thinking. diSessa (1987) hypothesizes a simple pattern-triggering process in which each situation activates an *ad hoc* collection of inference patterns, leading to inconsistent and unprincipled application of different ideas in different situations.

The protocol from S4 does not support the notion that her answers are generated solely by *ad hoc* collections of inference-patterns triggered by situation features. She frequently argues abstractly, ignoring the particulars of the situations she is asked to reason about. She tries hard to formulate explanations that will cover a wide range of facts. In the protocol excerpts quoted above she considers alternative hypotheses, rejects hypotheses that contradict the facts as she sees them, constructs *reductio ad absurdum* arguments, makes predictions, reasons counterfactually, and conducts thought experiments. If S4 is more primitive in her views about physical motion than professional physicists, it is because she has spent little time thinking about physical motion, not because her reasoning processes are primitive. A single example does not provide information about the population at large, but we believe it puts the ball in the other court: Those who argue that the typical student does not reason with the coherence and systematicity that characterizes theoretical thinking should feel obliged to provide empirical support for their claim.

Although our data do not support diSessa's specific theory of common sense beliefs, we nevertheless believe that his general point is important and valid: It is quite plausible that theoretical thinking involves cognitive processes that are not part of everyday cognition, and that such processes are crucial for the ability to change towards more advanced beliefs. For example, Hestenes (1987) has proposed a view of theoretical thinking in physics that is centered around the concept of modeling, a type of reasoning process that is not prominent in everyday thinking. Although the general claim that students do not think theoretically might turn out to be too strong, the specific hypothesis that students do not spontaneously think with models (in the sense defined by Hestenes, 1987) might still be valid. Other candidate processes might be found. For example, common sense seems to lack the notion of *successive approximations* that is so central to theoretical thinking in physics. The pedagogical implication of this type of hypothesis is that instructional programs for mechanics should teach the required reasoning processes. White (1987) has already tried an instructional program with a process-oriented component, with good results. But the basic research needed to identify the cognitive processes involved in conceptual change in mechanics is still ahead of us.

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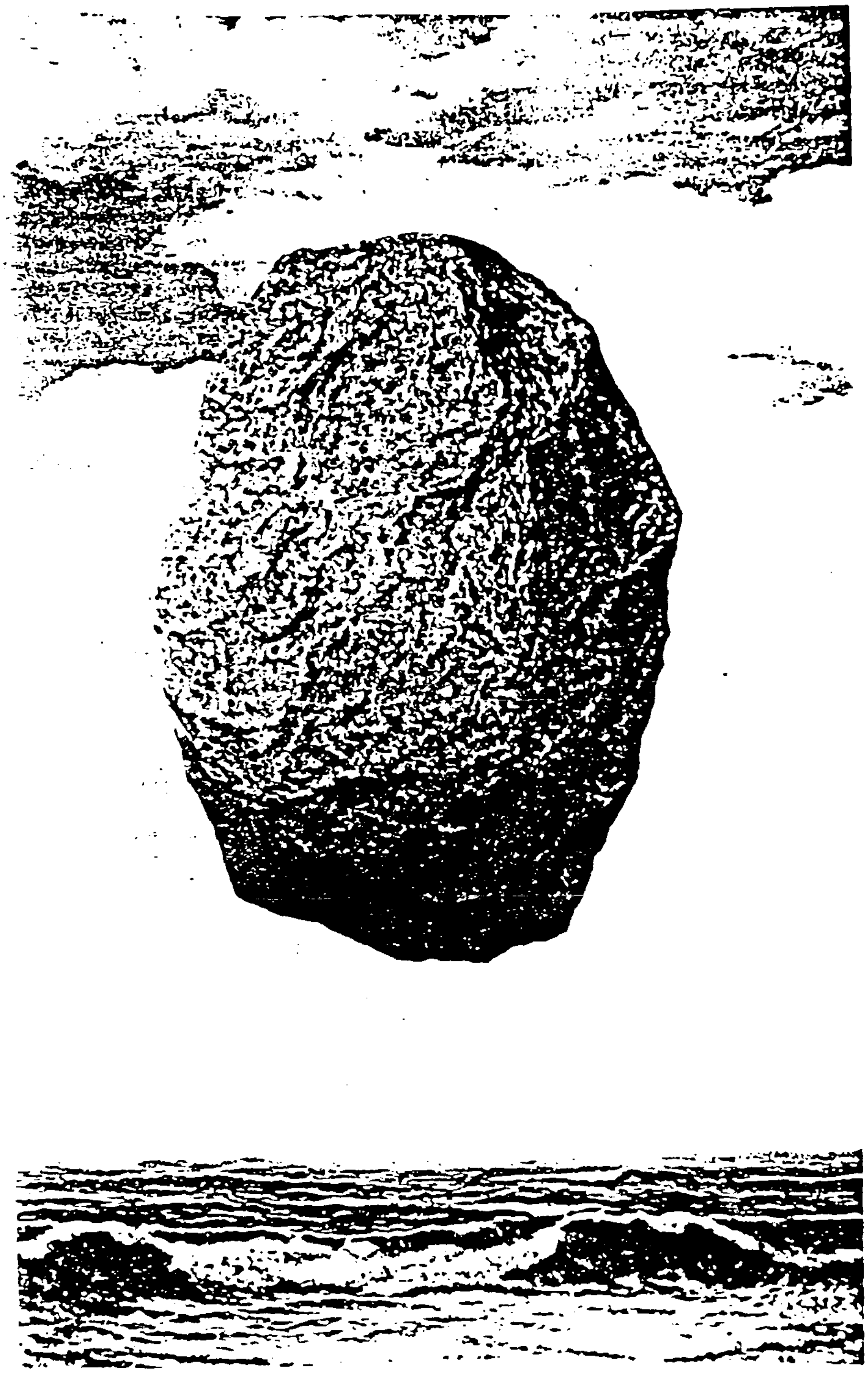
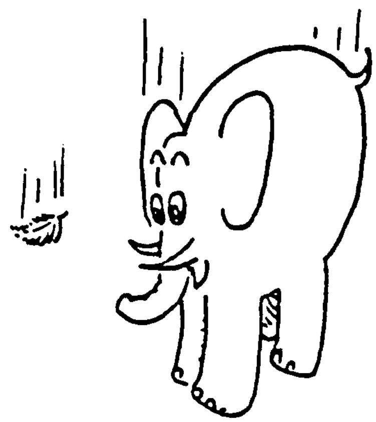
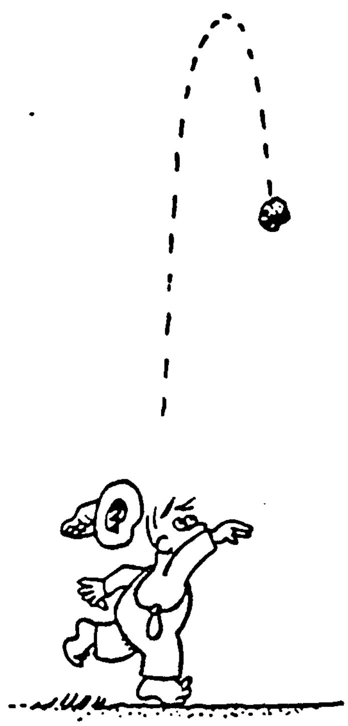
Appendix A: Pictures used in interview

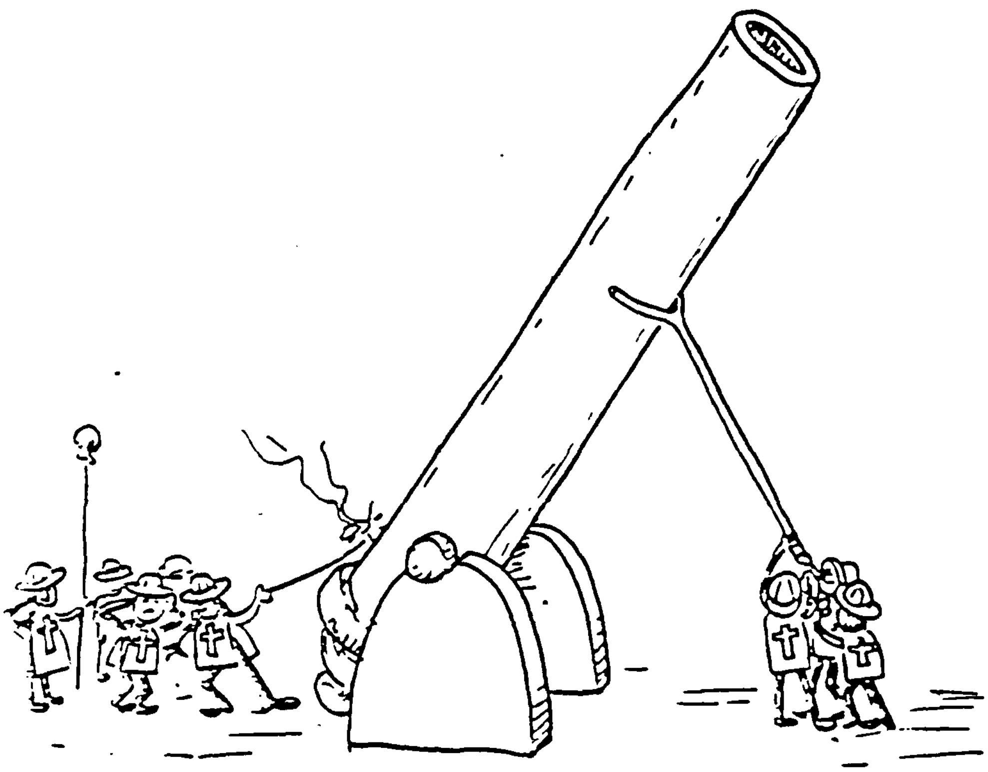
The following eight pages shows the pictures used in the interview to prompt the subjects to talk about physical motion. They show:

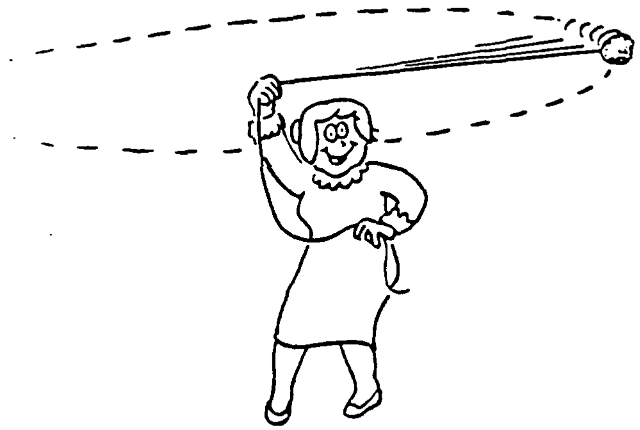
1. A large boulder suspended in the sky.
2. A plane flying in the air.
3. An elephant and a feather with dashed lines above each. The dashed lines give the appearance, cartoon-fashion, that the objects are falling.
4. A boy with a raised arm and a ball directly above him. Dashed lines between the boy and the ball indicate that he has just thrown the ball up in the air.
5. A cannon ball in front of a cannon. Dashed lines indicate that the ball has been shot from the cannon. The cannon is at an acute angle to the ground.
6. A person swinging a string or rope above her head. One end of the rope is in her hand and the other end is attached to a book-like object.
7. Two trucks at the top of two separate hills. One hill is steeper than the other. Each truck face the bottom of the hill.
8. A ball in a cylindrical tube. The ball is on the wall inside the tube.

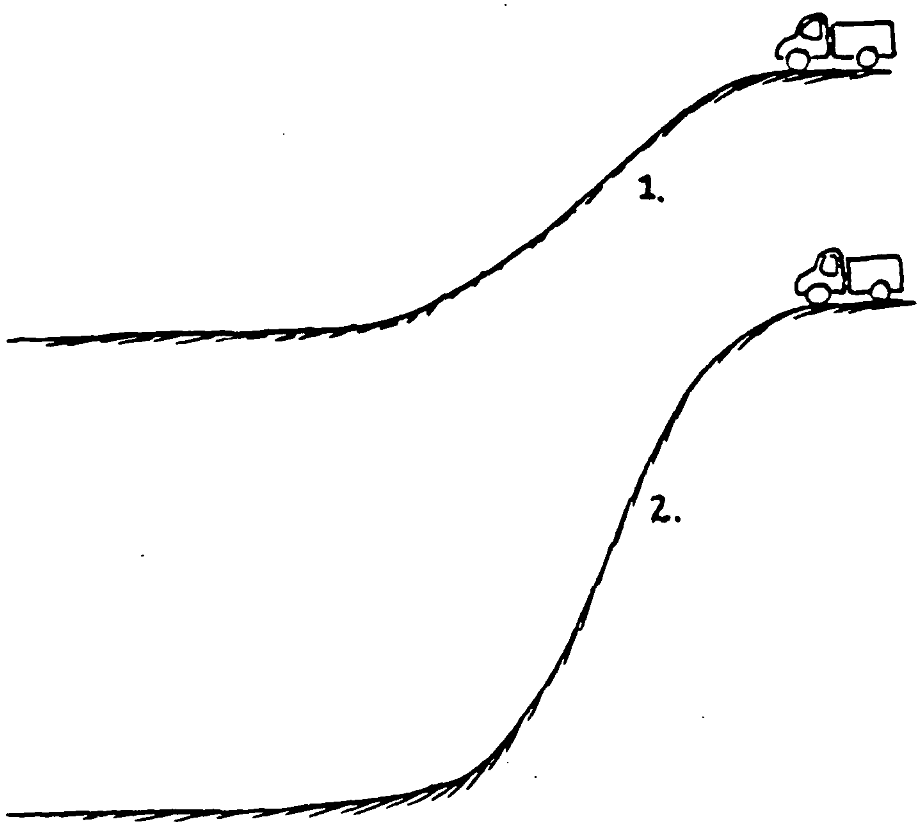








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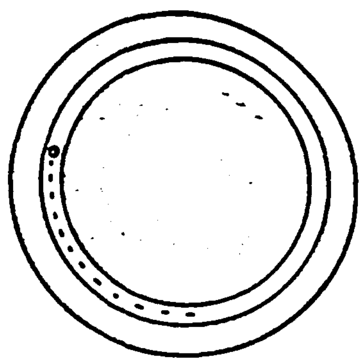

Appendix B: Complete list of S4's beliefs

The following is the complete list of 92 beliefs that we extracted from the protocol of the interview with subject S4 through the four-step method described on pages 7-10 in the text. We have grouped the beliefs into nine topics: (a) force and motion, (b) downward motion, (c) gravity, (d) projectile motion, (e) space, (f) rotation, (g) floating, (h) flying, and (i) miscellaneous. Within each topic, we have separated the beliefs into three subgroups: beliefs that we think Jean Buridan would have agreed with, beliefs which we think that Jean Buridan would have disagreed with, and beliefs for which we lack information about Buridan's position.

We have tried to give each belief a short but informative title, using some abreviations specially invented for the purpose. The notation "x/y/z" means that S4 uses the terms x, y, and z interchangeably. The symbol :: means "is proportional to". The symbol ::: means "is inversely proportional to". The symbol // means "is distinct from". Finally, the symbol --> means "leads to", "causes", or "implies", while <-- means "requires" or "presupposes".

The star * marks those beliefs that are the ten best supported beliefs for this subject (see the discussion of focussing on page 10). The ten best supported beliefs are belief no. 2, 3, 4, 8, 10, 13, 36, 42, 54, and 61.

A. Beliefs About Force and Motion

<u>Beliefs which S4 and Jean Buridan share:</u>

1. Motion <-- Force/Energy

An object moves as long as it has force/energy. When the force/energy stops, the object stops moving.

2. *Momentum/Force/Energy --> Motion

Imparted momentum/force/energy keeps an object moving after the source of the momentum/force/energy has ceased to act on the object.

3. *Agent Imparts Momentum/Force/Energy

An agent imparts momentum/force/energy to the object it acts on.

4. *Momentum/Force/Energy Accumulates During Downward Motion

An object that is moving downwards due to gravity accumulates momentum/force/energy.

5. Momentum/Force/Energy Continues After Force Stops

The momentum of an object continues after the force that acts on the object has stopped.

6. Resistance to Force/Energy :: Weight

The greater the weight of an object, the more it resists moving forces (other than gravity).

7. Motion <-- Unbalanced Force

In order for an object to move, one of the forces acting on it has to be stronger than its opposing force (if any).

8. *Motion <-- Force Stronger than Gravity

For an object to move (in any other direction than downwards), it must be propelled by a force that is stronger than gravity.

9. Fall --> Gravity the Stronger Force

Whenever an object is falling, gravity is stronger than whatever other force is acting on the object.

10. *Distance :: Momentum/Force/Energy

Stronger momentum/force/energy enables an object to travel a longer distance.

11. Duration of Imparted Motion ::: Resistance

The more resistance there is to the motion of an object down an inclined plane, the quicker the object stops (after the downward motion has ceased).

12. Dissipation --> Slower Speed

The speed of a moving object slows down as its momentum/force/energy dissipates.

Beliefs with which Buridan would disagree:

13. *Force/Energy Dissipates During Motion

Energy/force dissipates as it moves an object, unless it is replenished.

14. Force/Energy Dissipates with Zero Resistance

Energy/force dissipates even in the absence of resistance to the motion.

15. Forces Balanced --> No Motion

If two equal and opposite forces act on an object, the object is still.

Beliefs for which information about Buridan is missing:

None (in this category).

B. Beliefs About Downward Motion

Beliefs which S4 and Jean Buridan share:

16. Falling Object Accumulates Speed

A falling object accumulates speed.

17. Falling Affected by Object Type

The way in which an object falls is a function of what kind of object it is.

18. Falling Speed :: Distance of Fall

The greater the distance an object falls, the more speed it accumulates.

19. Falling Speed :: Weight

Heavier objects fall faster than lighter objects.

20. Falling Speed Function of Shape

The shape of an object affects the speed at which it falls.

21. Falling Speed Function of Density

The density of an object affects the speed with which it falls.

22. Wind Effect on Falling Speed ::: Weight

The wind slows down the fall of a heavier object less than the fall of lighter object.

23. Dense Medium Stops Falling

Objects that are falling stop when they come into contact with something that is dense enough.

24. Ground Stops Falling

When a falling object hits solid ground it stops moving.

25. Impact :: Momentum/Force/Energy

An object with more momentum/force/energy makes more of an impact when it hits something else.

26. Impact :: Falling Speed

An object which is falling faster will hit harder upon impact.

27. Impact :: Distance of Fall

The greater the height from which an object falls, the harder it falls.

Beliefs with which Buridan would disagree:

28. Falling Speed // Weight

Objects with different size/weight do not fall with different speeds.

29. Falling Speed ::: Wind

A wind that pulls in a different direction than the pull of gravity causes the speed of falling to decrease.

30. Impact :: Weight

The impact of a falling object (on the ground) is directly proportional to its weight.

31. Motion in U-Tunnel Stops

The motion of an object inside a U-shaped tunnel stops eventually.

Beliefs for which information about Buridan is missing:

32. Object Stops After End of Incline

An object that is going down an incline stops moving some time after it reaches level ground.

33. Incline Speed :: Angle of Incline

The greater the vertical angle of an incline, the more speed an object will acquire as it moves down the incline.

34. Object on Incline Accumulates Speed

An object that is moving down an inclined plane moves faster and faster.

35. Incline Speed ::: Resistance

The less resistance there is to an object's motion down an incline, the higher the speed the object will acquire.

C. Beliefs About Gravity

Beliefs which S4 and Buridan share:

36. *Gravity Pulls Down

Gravity pulls things down.

37. Gravity Pulls Towards Center of Earth

Gravity pulls objects towards the center of the earth.

38. Gravity Pulls on Objects with Weight

Gravity pulls on objects with weight.

39. Humans Can Resist Gravity

Human beings can move against gravity.

40. Limit on Resistance to Gravity

No matter how much force/energy a person has, there is a limit on how much he/she can resist gravity.

41. Strength of Gravity Varies

Gravity varies in the amount that it acts on something.

42. *Strength of Gravity ::Weight

The gravitational pull on an object is directly proportional to its weight.

43. Strength of Gravity //Shape

Gravity does not act differently as a function of shape.

44. Gravity -- >No Suspension

Gravity prevents objects from being suspended in midair.

45. Gravity Not produced by Air

The gravitational pull on objects inside the atmosphere is not produced by the air.

Beliefs with which Buridan would disagree:

46. Gravity Pulls From Center of Earth

Gravity is a pull from the center of the earth.

47. Gravity is Ubiquitous

Gravity acts on all objects at all times.

48. Gravity Acts Same on All Objects

Gravity acts the same on all objects.

49. Gravity Acts Same on Animate/Inanimate

Gravity acts the same on animate and inanimate objects.

50. Objects Cannot Resist Gravity

Inanimate objects cannot generate the force/energy required to resist gravity.

51. Gravity --> Fall

Objects fall down because gravity pulls on them.

52. Gravity Only Cause of Fall

Gravity is the only thing that makes things fall.

53. No Gravity --> No Fall

An object doesn't fall if it is outside the earth's gravitational pull.

54. *Gravity --> Objects Float

If there is no gravity, then objects float (in space).

55. Gravity --> No Weight

If there is no gravity, then objects are weightless.

56. Gravity is Magnetic Pull

Gravitational pull is a kind of magnetic pull.

Beliefs for which information about Buridan is missing:

None (in this category).

D. Beliefs About Projectile Motion

Beliefs which S4 and Buridan share:

57. Horizontal Projectile Drops to Ground

If an object is thrown parallel to the ground, it will drop to the ground (eventually).

58. Straight Up --> Straight Down

An object that is forced straight up will come straight back down.

59. Duration :: Distance

The greater the distance an object travels, the more time it takes.

Beliefs with which Buridan would disagree:

60. Direction Reversal --> Moment With Zero Speed

When an object turns around to move in the opposite direction, it has zero speed for a brief moment.

Beliefs for which information about Buridan is missing:

61. *Upward Path // Downward Path

The downward path of a projectile is not necessarily the same as the upward path.

62. Path Symmetry Depends on Force/Energy

Whether the downward path of a projectile is symmetrical to the upward path depends (in some unspecified way) on the force/energy.

63. Path After Hole Function of Direction

A rolling ball that drops through a hole in the surface it is rolling on takes a different path depending on whether it is rolling upwards or downwards when it hits the hole.

64. Horizontal Distance ::: Angle of Upward Path

The horizontal distance an object travels during projectile motion is inversely proportional to the vertical angle in which it is thrown.

E. Beliefs About Space

Beliefs which S4 and Buridan share:

None (in this category).

Beliefs with which Buridan would disagree:

65. Motion Stops in Space

The motion of an object in space stops at the point at which it would start falling, if it were on earth.

66. Distance in Space = Distance on Earth

A projectile travels the same distance in space, before it becomes suspended, as it would travel on Earth, before it starts falling.

Beliefs for which information about Buridan is missing:

67. No Weight in Space

Objects are weightless in space.

F. Beliefs About Rotation

Beliefs which S4 and Buridan share:

68. Rotator Determines Rotation

In rotational motion, the rotator determines the movement of the connector.

69. Human Can Cause Rotation

Human beings have an inherent ability to cause rotational motion.

70. Rotation Becomes Linear Motion

When the connector is cut in rotational motion, the rotatee follows a curved path for a short distance, and then continues to move in a straight line.

Beliefs with which Buridan would diagree:

71. Balance of Forces Change in Rotation

The relations between upwards, downwards, and sideways forces are continuously changing in rotational motion.

Beliefs for which information about Buridan is missing:

72. Rotatee Lags Rotator

In rotational motion, the rotated object lags behind the rotating object in time.

G. Beliefs About Floating

Beliefs which S4 and Buridan share:

None (in this category).

Beliefs with which Buridan would disagree:

73. Weight is Relative to Medium

The weight of an object is relative to the weight of the medium (water, air, or space) that it is in.

74. Objects Resurface in Water

Everything resurfaces to the top of the water after falling into water from a great height.

Beliefs for which information about Buridan is missing:

75. Water Density --> Floating Force

The density of water contains a force that gives objects the ability to rise to the surface of the water and to float.

76. Floating Ability ::: Weight

The lighter an object, the greater the ability it has to float. The heavier an object, the less ability it has to float.

77. Floating Force --> Less Falling Speed

The upward force of water slows down the speed with which an object falls through the water.

78. Floating Ability is Ubiquitus

Objects have a natural ability to float.

79. Floating Force Counteracts Gravity

Water produces a floating force that acts in the opposite direction of gravity.

H. Beliefs About Flying

Beliefs which S4 and Buridan share:

None (in this category).

Beliefs with which Buridan would disagree:

80. Take-Off <-- Force/Speed to Counteract Gravity

Take-off of a man-made objects requires force or speed sufficient to overcome the gravitational pull.

81. Staying Aloft Force :: Weight

The heavier the object, the more force/energy it takes to keep it in the air.

Beliefs for which information about Buridan is missing:

82. Take-Off Force :: Weight

The lighter the object the less force required to make it move against gravity.

83. Human Cannot Fly with Arms

Humans cannot fly by flapping their arms as wings.

84. Wings Propel Birds

Wings propel birds.

85. Take Off Force = Staying Aloft Force

That which keeps a flying object aloft is the same in kind as that which makes it take off.

86. Take Off w/o Force/Speed

Some animals and some machines can take off without great speed or force.

87. Wings Enable Flying

Wings provide a balance that allows objects such as planes and birds to fly.

88. Wings Not Sufficient for Flying

Wings are not sufficient for flying.

89. Wings Don't Keep Birds Aloft

Wings do not keep birds aloft.

I. Miscellaneous Beliefs

Beliefs which S4 and Buridan share:

None (in this category).

Beliefs with which Buridan would disagree:

None (in this category).

Beliefs for which information about Buridan is missing:

90. Meaning of "Further" and "Longer"

Vertical and horizontal distances are not really different, but they are referred to with different expressions.

91. Impact Can Shatter

An impact between two objects can shatter either object.

92. Shatter = Break Molecular Structure

An object shatters when something breaks its molecular structure.

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